DNAPL Invasion into a Partially Saturated Dead-end Fracture

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Introduction

Fractures in the unsaturated zone act as preferential pathways for the transport of water and contaminants such as dense nonaqueous phase liquids (DNAPLs). Although DNAPLs can quickly migrate through a connected fracture network, DNAPLs will inevitably encounter dead-end fractures where they become entrapped. The volume of DNAPL entrapped in these dead-end fractures could be large, which could have serious implications for site remediation.

This study investigates DNAPL entry into a partially saturated dead-end fracture. The theoretical criteria for DNAPL entry into a partially saturated dead-end fracture is presented and is followed by laboratory experiments conducted on an analog parallel plate fracture.

Criteria for DNAPL Entry

In this study, we are considering DNAPL entry into a partially saturated dead-end fracture that is filled with water uniformly across the width of the fracture, as shown in Figure 1.
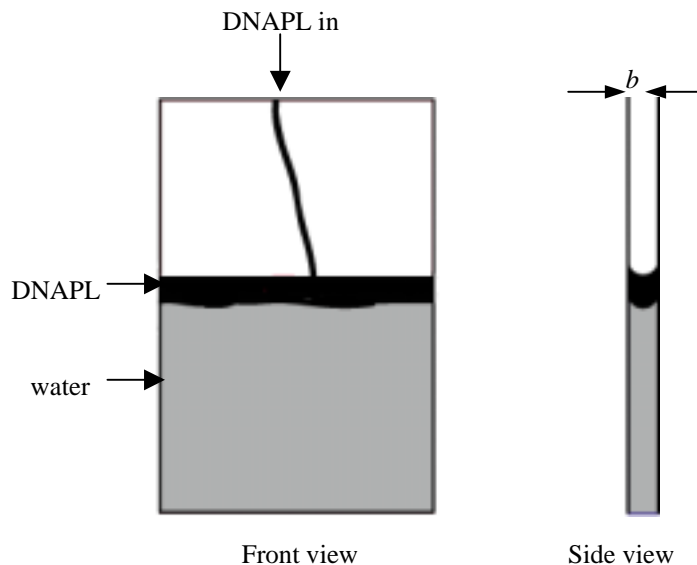

Figure 1.   Schematic of a partially saturated dead-end fracture and a DNAPL pool above the water.

DNAPL entry into a partially saturated fracture as illustrated in Figure 1 is similar to the scenario of DNAPL entry into the capillary fringe. The critical height for DNAPL entry, $h_{DNAPL,entry}$, into the capillary fringe is given by the following equation (Cohen and Mercer, 1993)

$$h_{DNAPL,entry} = \frac{2\sigma_{DNAPL/water} \cos\phi}{\rho_{DNAPL} gb} \qquad (1)$$

where $\sigma_{NAPL/water}$ is the interfacial tension between the DNAPL and water, ϕ is the wetting contact angle, ρ_{DANPL} is the DNAPL density, g is the gravitational acceleration, and b is the pore size or aperture width.

Equation 1 does not, however, account for the capillary force due to the DNAPL-air interface. This force can be incorporated into the criterion for DNAPL entry by performing a force balance of the DNAPL pool overlying the water. Assuming hydrostatic equilibrium, the pressure at the top of the water, $P_{water,top}$, is

$$P_{water,top} = \rho_{DNAPL} gh_{DNAPL} - \frac{2}{b}(\sigma_{DNAPL/air} \cos\phi_1 + \sigma_{DNAPL/water} \cos\phi_2) \qquad (2)$$

where h_{DANPL} is the height of the DNAPL pool above the water, $\sigma_{DNAPL/air}$ is the surface tension between the DNAPL and air, ϕ_1 is the wetting contact angle at the DNAPL/air interface, and ϕ_2 is the wetting contact angle at the DNAPL/water interface.

The DNAPL will not invade the water as long as the DNAPL/water curvature is concave up, which occurs when $P_{water,top}$ is negative. When the height of DNAPL reaches the critical pressure where $P_{water,top}$ becomes zero, the DNAPL will invade the water. The criterion for DNAPL entry therefore becomes

$$h_{NAPL,entry} = \frac{2}{\rho_{NAPL} gb}(\sigma_{NAPL/air} \cos\phi_1 + \sigma_{NAPL/water} \cos\phi_2) \qquad (3)$$

The critical heights for DNAPL entry calculated using Equations 1 and 3 will be compared to experimental observations.

Experimental Methods

Glass parallel plates with an aperture of 0.03125 cm were sealed with epoxy on the sides and bottom to create an analog dead-end fracture. The dimensions of the plates were 15.2 cm x 20.3 cm. Water was manually injected into the top of the fracture using a syringe to partially saturate the fracture. The injected water flowed to the bottom of the fracture and was injected until it filled about ¾ of the fracture volume. TCE dyed with oil red dye was injected manually into the partially saturated fracture using a syringe. Two experiments were performed. In the first experiment, TCE was injected slowly, but nearly continuously into the fracture until the TCE began to invade the water. Once the TCE began entering the water, the TCE injection was

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stopped. In the second experiment, TCE was slowly injected until the pool height above the water reached between 1.0 - 1.5 cm, but the TCE did not immediately enter the water. No additional TCE was injected to investigate whether or not the TCE would eventually invade the water. Observations from these experiments were recorded using a digital video camera. The TCE properties from the literature are: $\rho_{TCE} = 1460$ kg/m^3; $\sigma_{TCE/air} = 28.8$ mN/m; $\sigma_{TCE/water} = 35$ mN/m. Using these values and assuming a contact angle of zero, the critical height for TCE entry into the water is 1.6 cm using Equation 1 and 2.9 cm using Equation 3.

Results and Discussion

Experiment 1

In Experiment 1, TCE was injected nearly continuously into the fracture until the TCE began to enter the water. Once the TCE entered the water, the blob of TCE would flow to the bottom of the dead-end fracture. Figure 1 shows a sequence of images of the TCE entering the water. Note that when the TCE enters the water the pool of TCE attached to the invading finger is also pulled into the water.

The TCE height required to enter the water was measured from captured video images of the experiment. The corresponding volume of TCE that entered the water for each of these events was also measured. There did not appear to be any correlation with these two parameters. The average height of TCE for entry into the water is 1.7 cm, which is close to the critical height predicted by Equation 1.
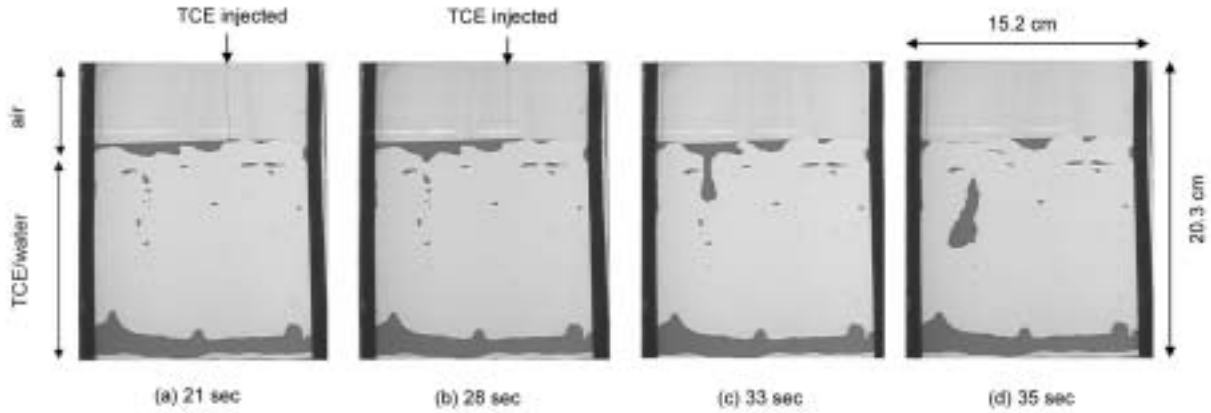

Figure 2.   Sequence of images of the TCE (dark gray) entering the partially saturated dead-end fracture. TCE accumulated at the bottom of the fracture is from previous injections. Time denotes seconds after TCE was injected to form the pool observed at the top.

Experiment 2

The purpose of Experiment 2 was to examine if the TCE would eventually invade the water when the height of the TCE was less than the critical height provided by Equation 1. TCE was slowly injected until the pool height above the water reached about 1 cm. After 10 minutes, the TCE pool had still not entered the water and after 20 minutes it was evident that the pool

height had decreased because the TCE had volatilized. The TCE pool was therefore immobile at a height of 1 cm. Since the TCE did not enter the water at this height, additional TCE was added to this pool until the height of it reached approximately 1.5 cm. The pool remained immobile for nearly 10 minutes, and then began to slowly redistribute itself, forming a finger of TCE. After reaching a height of 2.8 cm, the finger quickly entered the water, pulling the TCE pool connected to it. Another run was performed where TCE was injected until the pool height reached 1.5 cm and the TCE once again eventually invaded the water after slowly redistributing itself and forming a finger. The finger slowly increased in length until reaching 2.8 cm before the entire pool of TCE entered the water. The length of 2.8 cm is close to the critical height of 2.9 cm predicted by Equation 3.

The results of these two experiments indicate that DNAPL invasion into a partially saturated dead-end fracture (or the capillary fringe) can occur at two critical heights that are given by Equations 1 and 3. The critical height corresponding to Equation 1 applies when there is a nearly continuous supply of DNAPL. The second critical height corresponding to Equation 3 occurs when hydrostatic conditions are present. Experiment 2 also demonstrates that time is an important component of fluid instability in this air/DNAPL/water system. The DNAPL pool can remain immobile for a period of time before eventually redistributing itself and entering the water.

Reference

Cohen, R.M. and J.W. Mercer, DNAPL Site Evaluation, Boca Raton, Florida: C.K. Smoley, 1993.